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Depth and Source Mechanism Estimation for Special Event Analysis, Event Screening, and Regional Calibration

P. Goldstein
D. Dodge
G. Ichinose
A. Rodgers
J. Bhattacharyya
R. Leach

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Depth and Source Mechanism Estimation for Special Event Analysis, Event Screening, and Regional Calibration

Peter Goldstein, Doug Dodge, Gene Ichinose, Arthur Rodgers,
Joydeep Bhattacharyya, Richard Leach
Lawrence Livermore National Laboratory (peterg@llnl.gov)

We present an overview of methods for estimating depth and mechanism and summarize our recent efforts to use waveform modeling based depth and mechanism estimates for special event analysis, event screening, and regional calibration. We summarize the strengths and limitations of a variety of techniques and describe our on-going efforts to develop accurate high resolution depth and mechanism estimates by extending existing techniques and integrating methods that use different types of seismic data.

We describe a new tool that we've developed and validated that provides fast and accurate estimates of depth and mechanism based on far-regional to teleseismic (20^0 to 90^0) P-waveform modeling. Significant features of this tool include: its ability to provide accurate, high-resolution depth estimates ($\delta z<2$km) using a small number of stations. It also works well over a large range of depths including events that are very shallow ($z<1$km). It is applicable over a broad band of frequencies ($0\leq f\leq 2$ Hz) and magnitudes ($mb\geq 4.5$) and provides constraints on event mechanism including isotropic contributions. It also provides estimates of random and model errors and can be used to test hypotheses and investigate sensitivity to and trade-offs between model parameters.

We illustrate the utility of this technique for regional calibration, special event analysis, and event screening by comparing estimated depths and mechanisms of events in the Middle East and North Africa with those of the NEIC and by comparing our depth and mechanism estimates for selected events such as the May 11, 1998 India nuclear explosion and a November 8, 1991 earthquake that occurred in the same region.

We illustrate the advantage of combining different techniques for estimating depth and mechanism by comparing broadband (0-2Hz) far-regional and teleseismic body waveform modeling estimates of depth and mechanism with those obtained using intermediate to long period esitmates based on regional data. We show that the broadband body waves provide strong constraints on source depth and that both the broadband body waves and the intermediate to long period regional waves help constrain source mechanism.

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Introduction and Overview of Techniques

Depth and mechanism estimates for small- to moderate-size seismic events are useful for a number of reasons including special event analysis, event screening, and improved regional calibration for test ban treaty monitoring, improved understanding of regional earth structure and tectonics, and for characterization of regional wave propagation phenomena.

A variety of techniques have been used to estimate both depth and mechanism. Techniques that are primarily focussed on depth estimation include travel-time analysis of depth phases (e.g., Engdahl et al., 1998), cepstral analysis (e.g., Alexander and Yang .,1997), and observations of Rg waves (e.g., Bath, 1975, Kafka, 1990). Techniques that focus primarily on mechanism include first motion studies (e.g., Reasonberg and Oppenheimer, 19??) and studies of relative amplitudes of P and S phases (e.g., Pierce, 1980). Extensive work has been done on the development and utilization of techniques for estimating depth and mechanism from body and surface waveform modeling [e.g., *Dziewonski et al.*, 1981; *Wallace and Helmberger*, 1982; *Romanowicz and Guillemant*, 1984; *Lay et al.*, 1994; *Sipkin*, 1994; Goldstein and Dodge, 1999].

Although these studies have significantly improved our ability to estimate depth and mechanism of seismic events there is still significant work to be done, particularly for small to moderate magnitude events at regional distances. Table 1 summarizes some of the advantages and disadvantages of many of the techniques for estimation of depth and or mechanism. While each of these techniques has their advantages, there is currently no technique that can consistently be used to obtain accurate depths and mechanisms for small magnitude events.

The most common problems are due to limitations of the data, such as, poor SNR or limited resolution in the bandwidth available, inadequate coverage or significant restrictions on station coverage, and large uncertainties due to significant trade-offs between parameters and sensitivity to earth structure. The empirical nature of some techniques can also make it difficult to assess their transportability and sensitivity to or trade-off with other parameters. Sensitivity to magnitude and source complexity are generally only an issue for relatively large events.

Table 1. Advantages and disadvantages of depth and mechanism techniques

Broadband body waves	Accurate, high resolution depth. Mechanism includes isotropic term Random and model errors estimates Sensitivities and trade-offs Works with small # of stations	Far-regional to teleseismic No near source and reciever structure
Depth phase picking	Simple to apply	Difficult to identify phases
Measurements of Rg	Indicator of shallow depth	Near-regional Depends on Earth structure No mechanism
Cepstra	High resolution depth	Need high frequencies Sensitive to source mechanism No mechanism
First motion	Simple to apply	Difficult to measure Need many stations and good azimuthal coverage
Relative phase amplitudes	Probabilities for different mechanisms	Difficult to correctly identify phases. No Depth or model errors
Global moment tensor inversion	Extensive validation for large events. Depth and mechanism	Mb>~5.5. Limited depth resolution especially for shallow depths.
Regional moment tensor inversion	Accurate source mechanism including non-double couple. Applicable at relatively small magnitudes. Works with small # of stations	Limited depth resolution. Significant sensitivity to Earth model.

In this rest of this paper, we describe an approach for accurate high resolution depth estimation based on modifications of the well known technique of modeling the direct P-wave and free surface reflections (e.g., Stein and Wiens, 1986). We describe a new, interactive tool and show that it provides fast and accurate estimates of depth and mechanism, with well defined random and model errors, to magnitudes as low as mb $\cong$ 4.5. We summarize our use of this tool to obtain "ground-truth" estimates of depth and mechanism for a set of earthquakes in the Middle East and North Africa. We illustrate the potential of this technique for special event analysis and event screening by comparing estimated depths and mechanisms of the May 11, 1998 India nuclear explosion and a November 8, 1991 earthquake that occurred in the same region. Finally, we show that a combination of this technique and longer period full waveform modeling can provide significant constraints on source parameters.

Method

We employ a very efficient, modified version of the well-known technique of modeling the initial P-wave bundle, consisting of P, pP, and sP [e.g., *Pearce*, 1980; *Stein and Wiens*, 1986]. This technique is very well suited for estimating depth because the relative timing of the direct P-wave and the surface reflections pP and sP are linearly dependent on source depth h (e.g., $t_{pP} - t_P = 2\, h/\alpha$). Relative amplitudes of these phases are linearly related to the moment tensor elements and provide significant constraints on source mechanism (Figure 1).

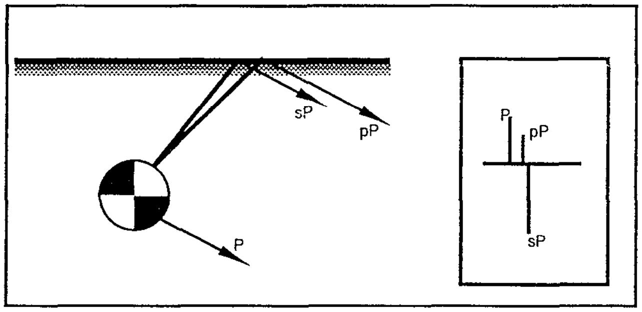

Figure 1. Relative timing of the direct P-wave and the free-surface reflections pP and sP constrain depth. Relative amplitudes of these phases help constrain mechanism.

The speed and accuracy of our technique are obtained via an extremely efficient implementation of the generalized ray synthetic algorithm [*Langston and Helmberger*, 1975]. Our implementation can calculate thousands of P-wave synthetics per second, so it is feasible to conduct exhaustive grid searches and to interactively experiment with different models.

Synthetics are calculated as a convolution of an attenuated source pulse with an impulse train consisting of appropriately delayed and scaled P, pP, and sP pulses:

$$S\,(t) = \mathbf{P} * [U^P\delta(t - t_p) + U^{pP}R^{pP}\delta(t - t_{pP}) + U^{sP}R^{sP}\delta(t - t_{sP})] \quad (1)$$

Here U^P, U^{pP}, and U^{sP} are source amplitudes, R^{pP}, and R^{sP} are reflection coefficients, t_p, t_{pP}, and t_{sP} are travel times, and $\mathbf{P}$ is the attenuated source pulse.

The source pulse is a triangle function with a rise time corresponding to that of an expanding circular crack with an adjustable prespecified stress drop (usually 30 bars) and moment (Mo) determined from the moment-magnitude relationship of [*Kanamori and Anderson*, 1975]. Magnitude is calculated using the median corner frequency from all the data. Corner frequencies are estimated from the maximum in the instrument-corrected, velocity power spectra. The user can also prespecify magnitude based on other data. Attenuation is accounted for by convolving an [*Futterman*, 1962] attenuation pulse with the source pulse. To solve for a best-fit depth and mechanism, our tool evaluates a misfit function between data and synthetics on a grid of depths and mechanisms and chooses the combination with the lowest residual as the solution. Further refinement of the solution is carried out using the simplex algorithm. The misfit function is:

$$R = \sum\,[1 - C_{max}(\text{data}_i,\text{synthetic}_i)]\, SNR_i\,/\,SNR_{avg} \quad (2)$$

where the sum is over N stations, $C_{max}(x,y)$ is the maximum of the normalized cross correlation of x and y, SNR_i is the ratio of mean signal amplitudes in user-set windows before and after the first arrival, and SNR_{avg} is the mean SNR for all the stations.

Our minimization strategy (Table 2) is extremely efficient because it computes synthetics by reading and multiplying precalculated terms from lookup tables. Separate tables are generated for source independent (R^{pP}, R^{sP}, t_p, t_{pP}, and t_{sP}) and path independent (U^P, U^{pP}, and U^{sP}) terms. The source amplitudes are of the form $U^{Phase} = \gamma_k^{\dagger}\,\mathbf{M}\,\gamma_l\,/c^3$. Where $\mathbf{M}$ is the moment tensor, γ_k is a direction vector of a phase along the ray at the source, and c is the velocity at the source.

Table 2. Outline of minimization strategy.

1. Compute table of P- and S-wave direction vectors at the source.
2. Compute table of travel times and reflection coefficient.
3. For each moment tensor **M**, a. Compute the source amplitudes U^{P}, U^{pP}, and U^{sP}. b. Compute synthetics at multiple depths. c. Cross correlate with data to find depth with smallest residual.

Uncertainties due to random errors are estimated using bootstrapping [*McLaughlin*, 1988]. Bootstrapping is used to estimate the mean and standard deviation of model parameters by treating random subsets of the modeled data as different realizations. Model parameters are estimated for each realization, and the mean and standard deviation of the model parameters are estimated from the distributions of model parameters. We restrict our bootstrapping analysis to a maximum of 30 realizations because it can be a very time consuming process. With this restriction, bootstrapped estimates of uncertainties can be obtained in less than ten minutes on a Sun Sparc Ultra 1 workstation.

Model error contributions to uncertainties in depth are relatively easy to calculate. Depth estimates (Z) are linearly related to the medium velocity (V) above the source, $Z = V^*(t_p - t_{pP})/2$. Therefore, uncertainties in depth (δZ) are also linearly related to uncertainties in velocity (δV).

$$\delta Z = \delta V^*(t_p - t_{pP})/2 \qquad \text{or} \qquad \delta Z = \delta V^* Z/V \quad (3)$$

If we assume uncertainties in velocity above the source are typically less than 15%, a fairly conservative estimate, model errors should be less than 15% of the estimated depth. We assume that errors in depth due to complexities in source time function [*Christensen and Ruff*, 1985] will usually be small for the small- to moderate-size events of interest to this study. Although laterally varying velocity structure could contribute systematically to uncertainties in depth, we expect that such complications are second-order effects.

Estimating potential systematic errors in mechanism is much more difficult. The primary measurements that determine mechanism are the relative amplitudes of the reflected waves pP and sP to P,

$$A_{pP-P} = [\gamma_2^{\dagger}\, \mathbf{M}\, \gamma_2] * R^{pP} / [\gamma_1^{\dagger}\, \mathbf{M}\, \gamma_1] \quad (4)$$

$$A_{sP-P} = [\mathbf{P}^{\dagger}\, \mathbf{M}\, \gamma_3] * R^{sP}\, \alpha^3 / [\gamma_1^{\dagger}\, \mathbf{M}\, \gamma_1]\, \beta^3 \quad (5)$$

Gamma and **P** are the radial and transverse direction vectors. The numerical subscripts correspond to (1) downgoing P-wave, (2) upgoing P-wave, and (3) upgoing S-wave. As indicated by these equations, mechanism is a complex function of the direction vectors and velocities at the source and the free-surface reflection coefficients. Given realistic estimates of near-source velocity variations, it should be possible to use a Monte Carlo analysis of the above equations to estimate potential systematic errors in mechanism. This is a subject of our ongoing work.

A Fast and Accurate Interactive Tool

Our new tool for estimating depth and mechanism (Figure 2) has a number of significant features. Foremost are its speed, validated accuracy, uncertainty estimates, improved depth resolution, and extended performance to smaller magnitudes. The tool is also integrated with an automated network magnitude estimator and easy-to-use, interactive filtering and first-arrival picking tools. It can also be run in batch mode. A user can interactively test hypotheses with a variety of source parameters and investigate the sensitivity of the solution to variations in individual source parameters.

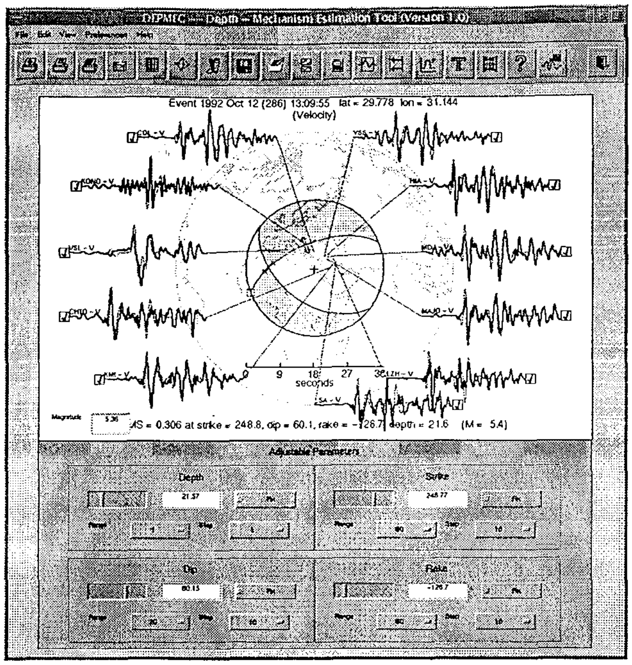

Figure 2. Main window of our new, interactive depth and mechanism estimation tool. Rapid estimates of depth and mechanism are obtained using grid search and simplex algor-ithms. Uncertainties are estimated using a bootstrapping procedure.

Based on experience thus far, this tool works well with data at far regional and teleseismic distances and can be applied to relatively high-frequency data (up to ~2 Hz). We have also successfully applied it to events with relatively low magnitude (mb ≅ 4.5). As part of our ongoing work, we will extend the capabilities of this tool to regional and near regional distances.

We have successfully analyzed events with tens of stations and as few as three stations; however, uncertainties are typically larger with a smaller number of stations. Solutions include an estimate of depth and the best double couple with an option to estimate an isotropic component of the moment tensor. Our error analyses indicate that depth can usually be estimated to an accuracy of a few km. Although complete mechanisms are sometimes poorly constrained, we usually find that at least two out of three of the mechanism parameters (strike, dip, rake) are well constrained.

Validation with "Ground-Truth" Data

In this section, we demonstrate that body waveform modeling is an accurate technique for estimating depth and mechanism by comparing results from our tool with estimates of depth and mechanism from well-calibrated local, regional, and global networks (Figure 3). We begin by comparing our estimated depths and mechanisms with those of a set of 15 "ground-truth" events (◆) whose depths and mechanisms were constrained by well-calibrated local and regional networks. These data include shallow explosions, a mine collapse, and earthquakes. We find excellent agreement between our estimated depths and mechanisms and those estimated from the local and regional network data (Figure 4). Since all of the events in our "ground-truth" data set were shallower than 20 km, we applied our tool to an additional set of 25 deeper events (■) whose depths had been constrained with global network data and a global probability model for identifying secondary phases such as pP and sP [*Engdahl et al.*, 1998]. We find generally good agreement between our estimated depths and those obtained by Engdahl et al., (1998). In most cases where there are discrepancies, synthetics based on our depth and mechanism provide a much better fit to the data. However, the waveforms of a small number of events show evidence of source or path complexity that is not modeled very well by any depth and mechanism or by our simple source and earth structure model.

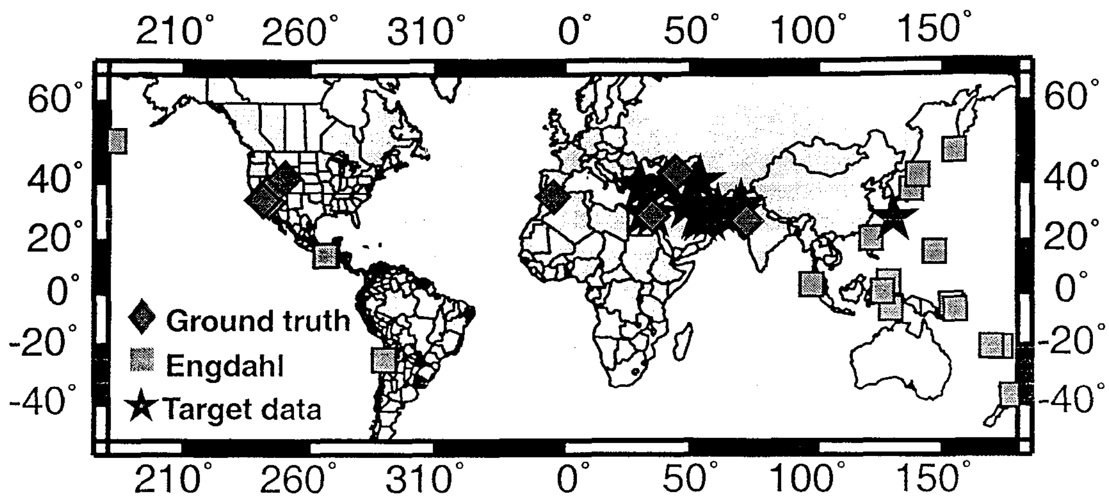

Figure 3. Map indicating the locations of our ground-truth events (◆), Engdahl et al., (1998) data subset (■), and Middle East and North Africa events (★).

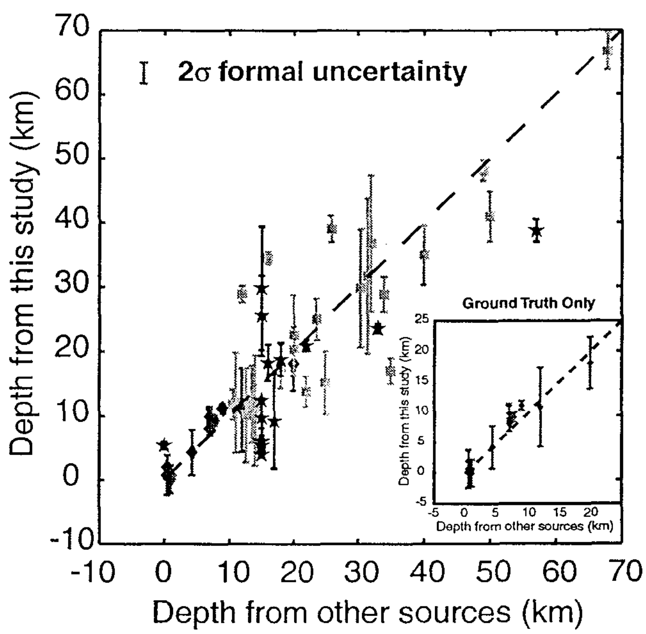

Figure 4. Comparison of our estimated depths with "ground-truth" depths (◆), Engdahl et al.'s (1998) estimated depths (■), and PDE depths (★). The excellent agreement between our depths and those of our "ground-truth" events (inset) suggests that this technique can be used to develop "ground-truth" when depth estimates from local and regional data are not available.

Developing "Ground-Truth" for Regional Calibration

The above results indicate that our new depth and mechanism estimation tool can provide accurate estimates of depth over a broad depth range. For well-recorded events, uncertainties in depth are relatively small (less than a few km). Based on these results, we apply this tool to a set of events in the Middle East and North Africa (■) and obtain estimates of depth and mechanism that should be useful as "ground-truth" for future monitoring-related research in this area. Estimated depths for these data are compared with those from NEIC preliminary determination of epicenters catalog in Figure 4.

Special Event Analysis and Event Screening for a CTBT

The ability to confidently state that a seismic event was not a man-made explosion is an important part of a CTBT monitoring system. Such screening capabilities are important for dealing with unusual or suspect events and are essential given the large number of events that it will be necessary to process. One of the fundamental parameters for event screening is depth. Tools such as the one we describe in this paper should be particularly useful for such screening because they can provide accurate estimates of depth, and it is unlikely that events with depths greater than a certain threshold, say 5 km, would be explosions. As examples, we compare the May 11, 1998 nuclear explosion in India and a November 8, 1991 earthquake from the same region (Figure 5). Our analysis indicates a very shallow depth for the May 11, 1998 event. If this event had not been announced, results from such an analysis would have been strong motivation for additional investigation. In contrast, the November 8, 1991 earthquake is much deeper and would have been of relatively little concern from a monitoring standpoint.

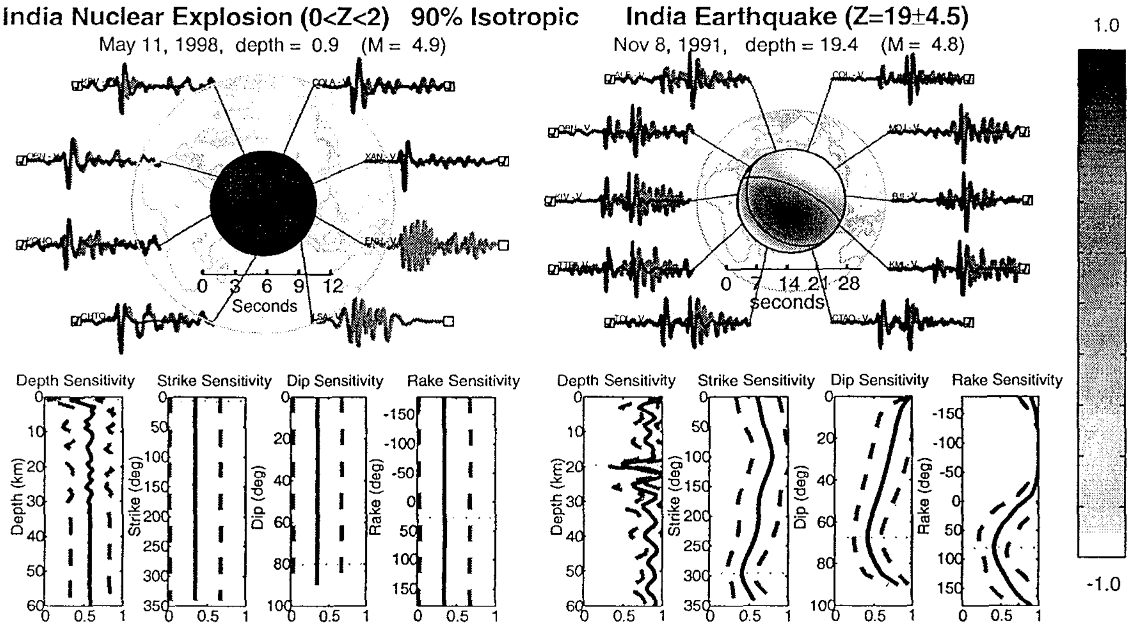

Figure 5. Comparison of waveforms and synthetics for a nuclear explosion (top left) and an earthquake (top right) in India. The sensitivity of the minimized residuals (solid line) and its variance (dashed lines) due to changes in the estimated parameters are shown at the bottom of each plot. The focal mechanism first motion, relative amplitudes are indicated by color beach ball plots. If the nuclear test (left) had not been announced, the estimated shallow depth ($Z < 2$ km) and large isotropic component of the moment tensor would have been strong motivation for additional analysis. In contrast, the earthquake (right) is much deeper and of relatively little concern from a monitoring standpoint.

Combining Techniques

In this section, we compare results from broadband body waveform modeling and intermediate period full waveform modeling and show that in combination they provide more accurate constraints on source mechanism. We compare solutions for the Mb 5.5, April 14, 1995 Western Texas event. Even though both methods provide excellent fits to the data, we show that each method is has greater sensitivity to selected parameters. For example, body waveform modeling is particularly sensitive to depth and provides a depth estimate of 18 km with a combined random and model uncertainty of less than 2 km (Figure 6). Uncertainties in strike dip and rake are approximately 100^0, 20^0, and 40^0, respectively.

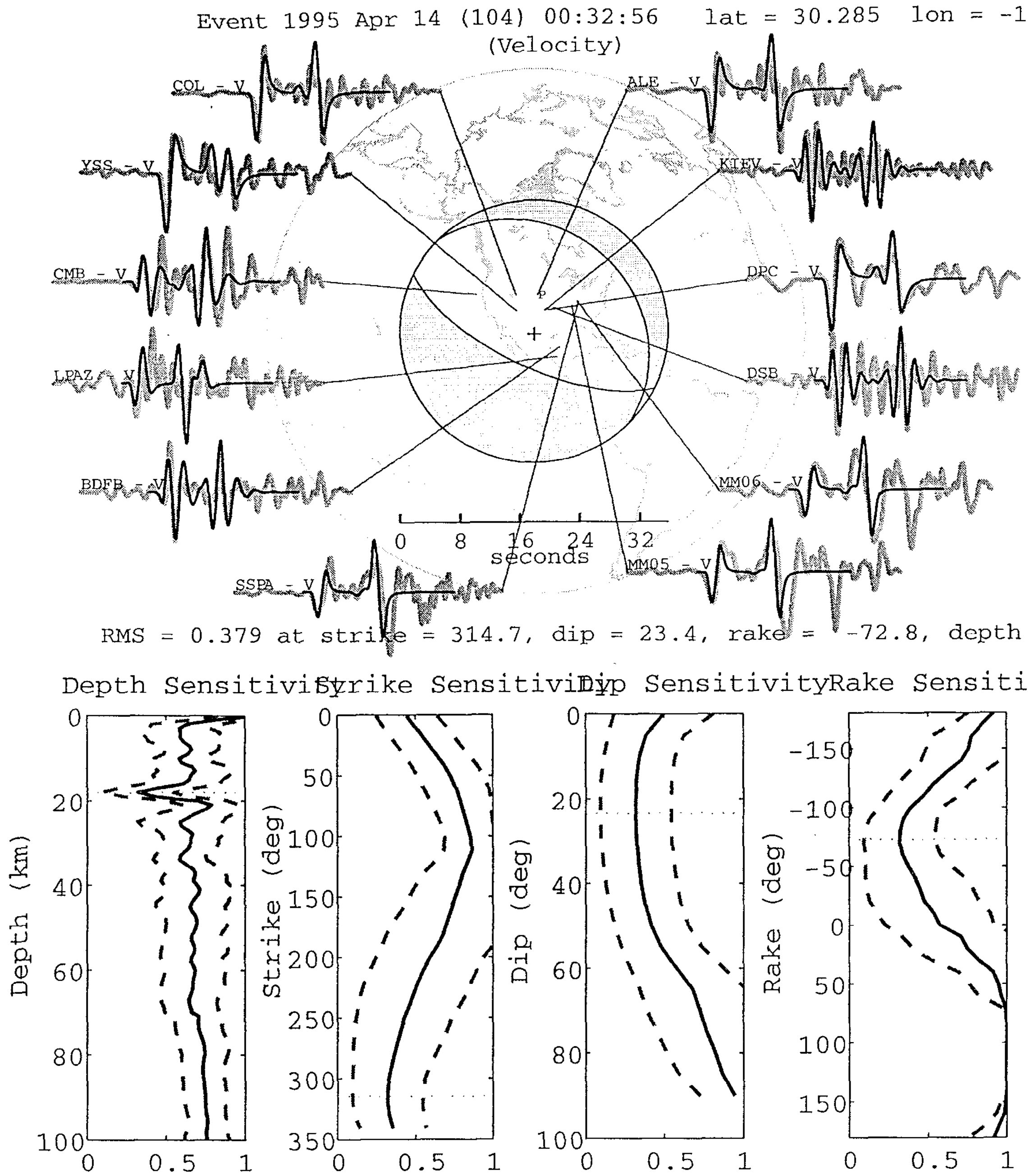

Figure 6. Broadband body waveform modeling solution for depth and mechanism of the April 14, 1995 Western Texas event.

Results from the intermediate-period, regional waveform modeling (Figure 7) are also consistent with a depth of around 20 km but have limited resolution of this parameter. In constrast, the sentivity of the solution to strike and rake suggest that these parameters are well resolved. Resolution of the dip appears to be similar for both methods. Further work is needed to develop complete error estimates for the regional solutions.

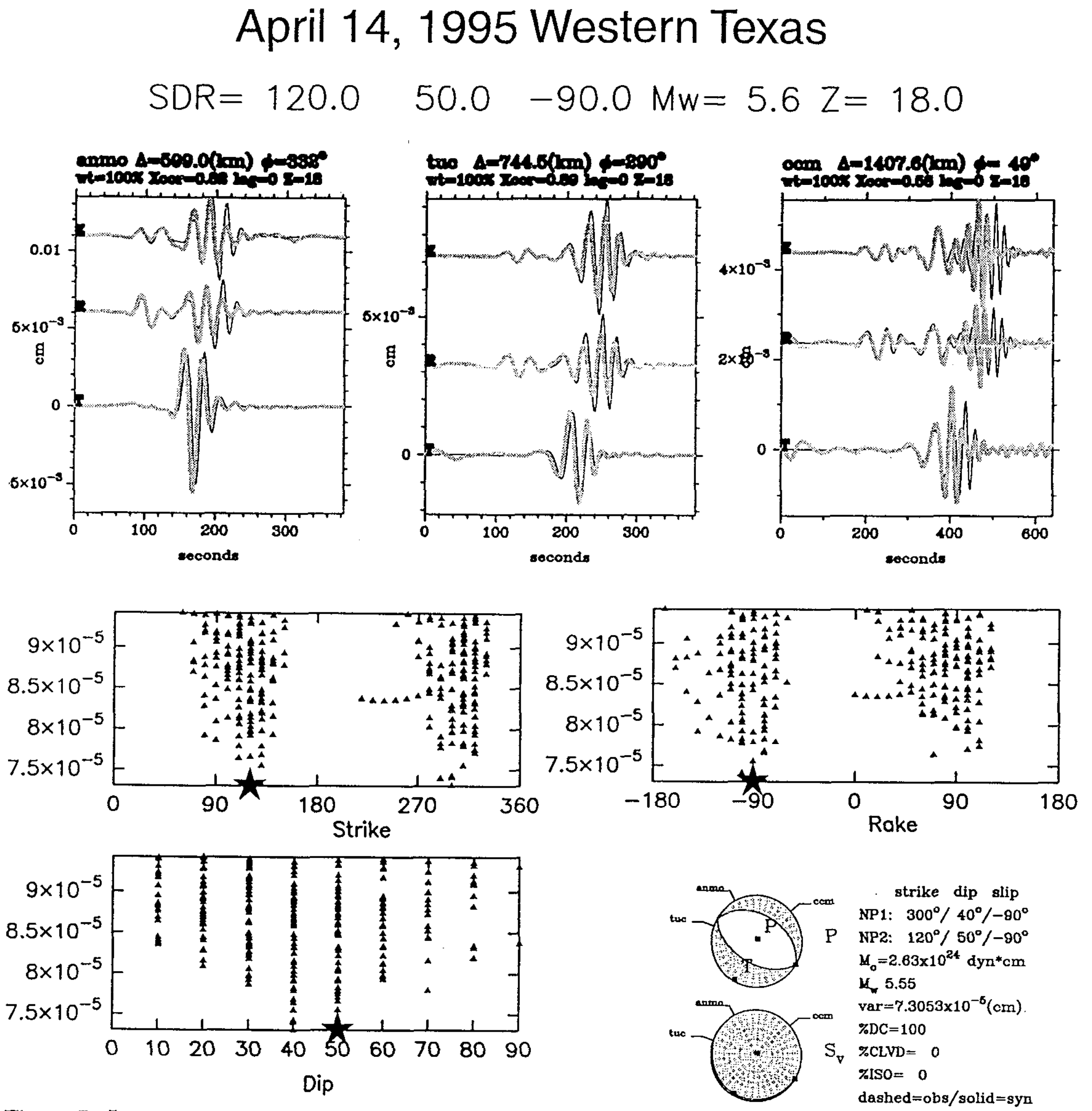

Figure 7. Intermediate period, regional waveform modeling solution for depth and mechanism of the April 14, 1995 Western Texas event.

Conclusions and Recommendations

We have summarized the advantages and disadvantages of a variety of techniques for depth and mechanism estimation and suggest that significant work remains to be done for events with magnitudes of interest for test ban monitoring. We also describe a new, waveform modeling-based tool for fast and accurate, high-resolution depth and mechanism estimation. Significant features of this tool include its speed and accuracy and its applicability at relatively high frequencies. These features allow a user to rapidly determine accurate, high-resolution depth estimates and constraints on source mechanism for relatively small magnitude (mb~4.5) events.

Based on the accuracy of depth estimates obtained with this tool, we conclude it is useful for both the analysis of unusual or suspect events and for event screening. We also find that this tool provides significant constraints on source mechanism and have used it to develop "ground-truth" estimates of depth and mechanism for a set of events in the Middle East and North Africa. These "ground-truth" depths and mechanisms should be useful for regional calibration.

Finally, we compare our far-regional to teleseismic body waveform modeling results with those from intermediate period regional data and show that a combination of such methods can provide significant improvements in source parameter estimation capabilities.

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References

Alexander, S.S., and C.C. Yang, "Accurate depth determinations and other diagnostic event characteristics in near-real time from regional signals", Proceedings of the 19th annual seismic research symposium on monitoring a CTBT, Annapolis, MD, September 23-25, 1997.

Christensen, D. H., and L. J. Ruff, "Analysis of the Trade-Off Between Hypocentral Depth and Source Time Function", *Bull. Seis. Soc. Am.*, *75* (#6), 1637–1656, 1985.

Dziewonski, A. M., T. A. Chou, and J. H. Woodhouse, "Determination of Earthquake Source Parameters from Waveform Data for Studies of Global and Regional Seismicity," *J. Geophys. Res.*, *86* (#B4), 2825–2852, 1981.

Engdahl, E. R., R. Vanderhilst, and R. Buland, "Global Teleseismic Earthquake Relocation With Improved Travel-Times and Procedures For Depth Determination", *Bull. Seis. Soc. Am.*, *88* (#3), 722–743, 1998.

Futterman, W. I., "Dispersive Body Waves," *J. Geophys. Res.*, *67* (#13), 5279–5291, 1962.

Goldstein, P., and D. Dodge, (1999) "Fast And Accurate Depth And Source Mechanism Estimation Using P-Waveform Modeling: A Tool For Special Event Analysis, Event Screening, and Regional Calibration", Geophys. Res. Lett. 8/15/99.

Kanamori, H., and D. L. Anderson, "Theoretical Basis of Some Empirical Relations in Seismology," *Bull. Seis. Soc. Am.*, *65* (#5), 1073–1095, 1975.

Langston, C. A., and D. V. Helmberger, "Procedure For Modeling Shallow Dislocation Sources," *Geophysical Journal of the Royal Astronomical Society*, *42* (#1), 117–130, 1975.

Lay, T., J. Ritsema, C. J. Ammon, and T. Wallace, "Rapid Source-Mechanism Analysis of the April 29; 1993 Cataract Creek (Mw = 5.3); Northern Arizona Earthquake," *Bull. Seis. Soc. Am.*, *84* (#2), 451–457, 1994.

McLaughlin, K. L., "Maximum-Likelihood Event Magnitude Estimation with Bootstrapping for Uncertainty Estimation," *Bull. Seis. Soc. Am.*, *78* (#2), 855–862, 1988.

Pearce, R. G., "Fault Plane Solutions Using Relative Amplitudes of P and Surface Reflections: Further-Studies", *Geophysical Journal of the Royal Astronomical Society*, *60* (#3), 459–487, 1980.

Romanowicz, B., and P. Guillemant, "An Experiment in the Retrieval of Depth and Source Mechanism of Large Earthquakes Using Very Long-Period Rayleigh-Wave Data," *Bull. Seis. Soc. Am.*, *74* (#2), 417–437, 1984.

Sipkin, S. A., "Rapid-Determination of Global Moment-Tensor Solutions", *Geophys. Res. Lett.*, *21* (#16), 1667–1670, 1994.

Stein, S., and D. A. Wiens, "Depth Determination For Shallow Teleseismic Earthquakes: Methods and Results," *Reviews of Geophysics*, *24* (#4), 806–832, 1986.

Wallace, T. C., and D. V. Helmberger, "Determining Source Parameters of Moderate-Size Earthquakes from Regional Waveforms," *Phys. Earth Planet Inter.*, *30* (#2-3), 185–196, 1982.